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Integration of a Photovoltaic System with an Electric Heat Pump and Electrical Energy Storage Serving an Office Building

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ABSTRACT

A renewable-based system able to meet pure electric, space heating and cooling loads of a small office building located in Southern Italy is evaluated here. The proposed energy conversion system is based on a photovoltaic plant, an electric-driven heat pump and electrical energy storage. Energy and environmental performance of this system has been evaluated by means of a dynamic simulation software changing photovoltaic nominal power (4.5-7.5 kW), battery capacity (3.2-9.6 kWh), and reference electrical system. The aim of the paper is the energy and environmental comparison on monthly, as well as, on yearly basis between the proposed system and the reference conventional system. The conventional system is based on the power grid, a natural gas fired boiler and an electric-driven chiller. The analysis here reported shows how monthly variation of electric reference system, due to different monthly Italian electricity mix production, influences the energy and environmental performance of the solar-based system. The proposed system guarantees high primary energy saving and equivalent carbon dioxide emissions reduction up to about 93%.

KEYWORDS

Photovoltaic, Electric heat pump, Electrical energy storage, Energy saving, Carbon dioxide emissions reduction, Renewable energy.

INTRODUCTION

In 2012, space cooling and heating final energy demand in domestic and service sectors for EU28 was about 3,481 TWh, which corresponds to 27.1% of total final energy demand [1]. In particular, in EU28 tertiary sector, space heating requires 681 TWh while for space cooling the demand is 105 TWh. In details Italy presents a final energy demand for space cooling and heating in service sector of 92.3 TWh, of which 67.4% is for space heating and 31.6% for space cooling [1]. High energy demand in service sector due to

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space cooling and heating demands has led to an increasing attention to the saving of primary energy and to the reduction of the related greenhouse gas emissions.

Different ways could be considered to obtain these results: in the last decade great efforts have been concentrated in the use of renewable technologies. Solar thermal Heating and Cooling (SHC) plants have been evaluated for tertiary field applications [2] considering adsorption [3] or absorption chillers [4]. A solar-activated system to meet cooling and heating loads could be made up with the introduction of a Photovoltaic (PV) plant feeding an Electric-driven Heat Pump (EHP). In 2016, the cumulative installed power of PV panels has been reached in Italy the value of 19.3 GW. PV electricity delivered in 2016 was 22.1 TWh, corresponding to 7.2% of global Italian electricity final demand [5]. In 2016, a percentage equal to18.9% of electricity delivered by PV plants was used on-site and the remaining share was exported to the power grid [6].

The above reported data on Italian PV electricity use show that the on-site exploitation of electric energy is very low, and raises attention to the technologies able to increase it. One of these technologies is the EHP that allows to cover space cooling and heating demands in buildings. Different applications of PV-EHP system, on the basis of the end user (office, commercial, school, residential, etc.), could be considered.

Huang *et al.* [7] presented an energy and economic analysis both for PV-based and solar thermal-based systems to meet heating and cooling demands of residential building in a hot-summer and cold-winter zone in China. PV plant has a peak power of 15.6 kW, while the rated cooling capacity of the two electric heat pumps is 28 kW and 65 kW respectively, and the rated heating capacities are 30 kW and 69 kW. The average nominal Energy Efficiency Ratio (EER) values were taken equal to 2.82 for cooling operating mode and Coefficient of Performance (COP) was chosen equal to 3.11 for heating operation. An annual primary energy saving of 30.7% is achieved by PV-based system, while the payback time is lower than 7 years.

Bilir and Yildirim [8], a school building located in Izmir (Turkey) was taken into consideration. An energy, economic and environmental analysis of PV-based system was carried out. This system is used to satisfy pure electric load as well as heating and cooling demand by means of an EHP. The authors considered two PV plant sizes (36-53 kW). On a yearly basis, the coverage ratio is 110% for Case 1 (36 kW) and 162% for Case 2 (53 kW). A simple payback of 7.9 years and 7.6 years, for Case 1 and Case 2 respectively, has been obtained. The energy payback time for both systems has been found as 5 years, while the greenhouse gas emission payback time is 2.7 years when compared with coal-based power plant electricity and 5.9 years when compared with natural gas based power plant electricity.

Solano *et al.* [9] analyse the electricity demand for an EHP interacting with a PV plant serving a commercial building located in Quito and Guayaquil (Ecuador). The PV system has been sized to meet electric energy required by EHP. For both locations, depending on the orientation of the building, different PV sizes (30-154 kW) were considered. Results show that the PV plant could guarantee an annual economic saving higher than 50% with a simple payback time between 10 and 30 years.

In [10], the authors use a cost-optimal method to design a PV plant serving a farm hostel located in Enna (Italy). Energy demand considered here includes space heating and cooling served by an air to water heat pump, as well as appliances, lighting and office devices. In this paper the solution proposed can guarantee a lifecycle cost reduction of 11% and a corresponding primary energy saving of 67%, with respect to the reference plant without renewable contribution.

To further increase the on-site use of electricity available from PV panels, different energy storage technologies could be considered. The main solutions could be based on a thermal energy storage interacting with an EHP or on an Electric Energy Storage (EES) linked to PV plant.

To improve the flexibility of PV-based system Romaní *et al.* [11] investigated a PV plant coupled to a heat pump supplying heat to a radiant wall as a system to reduce the imported electricity from the grid for heating and cooling purpose of buildings. The authors proposed the introduction of a radiant wall working as a thermal storage system allowing the accumulation of the PV output and, thus, the peak load shifting. Results derived from the analysis performed by the authors showed that charging the wall with solar energy resulted in higher overall energy use of the heat pump, while the imported grid energy was significantly reduced, thanks to the improvement of on-site use of PV electricity.

Schwarz *et al.* [12] focused their attention on a residential quarter located in Southern Germany with a PV-based system (36-73 kW). The authors evaluate how electric heat pumps as well as thermal and electrical energy storages can improve on-site use of PV electricity. The paper analyses the impact of different tariffs (unitary standard fixed, dynamic, and a capacity pricing scheme) on the investment and operation decisions and also the interaction of renewable system with the external power grid. Considering different scenarios it appears that the on-site use of electricity varies between 58 and 75%. Furthermore, the authors investigate how the demand side flexibility can improve PV contribution finding that for each configuration is better to act on thermal energy storage than on electric energy storage.

PV plants are normally grid-connected but to avoid issues to the interaction with the power grid could be interesting to use off-grid plant as investigated by Carriço *et al.* [13].

Different researchers investigated energy conversion systems serving office buildings based on PV panels that can also integrate battery storage and interact with an EHP [14-22].

In Aguilar *et al.* [14], an experimental analysis on an air-to-air heat pump unit powered using both a PV plant and the power grid has been performed. The control system gives priority to the renewable plant in order to maximise the on-site use of electricity. PV peak power is 705 W while EHP has cooling power of 3.52 kW (EER = 4.09) and heating power equal to 3.81 kW (COP = 3.83). The plant has been used for an office building with 35 m^2 in Alicante (Spain). The solar contribution, defined as the ratio between electricity available from PV and total electric demand of the office, is about 65%.

A PV-based system that integrates an EHP satisfies electric, cooling and thermal loads of a building used for office purpose in Naples (Italy) was investigated in Roselli *et al.* [15]. This energy conversion system has been evaluated through the dynamic simulation software TRNSYS. Performance on energy, as well as on economic and environmental basis of the system, changing different variables (PV nominal power, panel tilt angle, natural gas and electricity specific price), were evaluated. The proposed system leads to a saving in terms of primary energy and to a lowering of equivalent Carbon dioxide (CO_2) emissions up to 81% when matched to a conventional reference system consisting of Italian electric power grid, an electric-driven chiller and a gas-fuelled boiler.

The system introduced in Roselli *et al.* [15] was subsequently analysed adding electric energy storage [16]. The introduction of battery leads to an abatement of electricity feeding the power grid but the high first cost of this equipment affects the economic results. A further way to improve the on-site use of PV electricity could be the use of a "mobile storage" represented by an Electric Vehicle (EV) as investigated in [17, 18] starting from the system proposed in Roselli *et al.* [15]. In particular in Roselli and Sasso [17], the authors performed an energy and environmental analysis varying PV peak power, EV charging mode and daily distance aiming the increase of on-site use of electricity available from PV plant. The introduction of an EV leads to a higher electricity demand, even if the on-site use of PV electricity improves.

In Roselli *et al.* [18], an energy analysis on annual basis of three scenarios based on PV and EHP was considered: the first one without electric energy storage, the second one with an electric energy storage (9.6 kWh) and the third scenario with the introduction of an EV (120 km/day). The analysis was carried out varying only PV plant size. The solution guaranteeing the highest on-site use of renewable electricity was that one characterized by the use of electric energy storage.

Hartmann *et al.* [19] analysed by means of TRNSYS a system characterized by a PV plant activating an electric-driven chiller that meets electric and cooling demand of a low size office building located in Freiburg (Germany) and Madrid (Spain). The authors reported an economic and energy analysis of the solar system changing PV panel area. The performance improves with PV collecting area reaching a saving of primary energy up to about 40% for the city of Freiburg and about 60% for the plant supposed to be located in Madrid.

An analysis performed on experimental and theoretical basis on a system composed by PV collectors (2.88 kW), an EHP and an EES (250 Ah) has been reported in Izquierdo *et al.* [20]. EHP with a rated thermal power equal to 6 kW, meets space heating load of a small laboratory built in Spain.

An energy and environmental analysis on a solar-based system has been performed by Izquierdo *et al.* [21]. The study starts from experimental data of a system consisting of PV modules (2.16 kW), an EES (250 Ah) and an EHP, with a rated thermal power equal to 6 kW, that covers demand for space heating of a lab situated in Spain.

A field test on a system consisting of a stand-alone solar PV system, an EES and an electric-driven chiller has been considered in Huang *et al.* [22]. The system meets the requirements of a low-energy demand building with an average U-value of the building envelope of 0.22 $Wm^{-2}K^{-1}$. The tests on six system layouts were carried out evaluating actual and daily performance. The results show that an improved battery storage size and inverter that integrates Maximum Power Point Tracker (MPPT) technology have to be introduced to increase the performance.

The above reported papers show a focus on simulative or experimental studies of solar activated heating and/or cooling systems for buildings mainly considered for office purpose. The energy conversion systems introduced in these studies are characterized by the presence of an electric-driven heat pump or electric-driven chiller and a PV plant. These papers report the results for specific days, or on seasonal and annual basis. According to the best knowledge of the authors no paper investigates how the monthly variation of power grid mix for such systems can affect the primary energy saving and reduction of CO_2 emissions. The approach normally considered in the above reported literature review is based on the introduction of average annual performance factor affecting power grid. The proposed approach can affect the performance of the analyzed systems, and in particular the performance of electric-driven heat pump subsystem. The primary energy linked to this equipment depends not only by outdoor air temperature but also by electricity mix that is not constant but varies on monthly basis.

Hereinafter, a PV field that activates an air to water EHP covering space cooling and heating load of a small office building in Naples (Southern Italy) is analysed on monthly and annual basis evaluating energy and environmental performance parameters. The aim of this paper is to understand how the monthly variation of electric Italian reference power grid efficiency can influence the performance of solar-activated systems. The analysis is carried out analysing two scenarios: the first consisting of PV-EHP system only, while the second is upgraded also by an EES. The importance in introducing lay-out system able to increase on-site use of PV electricity to meet building demand is also analysed in this paper. The reduction of PV electricity feeding the electric grid is an element often underestimated. Indeed the energy policy needs to be oriented towards the improvement of on-site use of electricity available from renewables. Solar based system proposed in this paper can guarantee satisfactory saving in terms of primary energy and reduction of equivalent CO_2 emissions up to about 93%. By adding electric energy storage the contribution of external grid, that is always present, can be alleviated.

METHODS

This paragraph reports the methods put forward to evaluate the Proposed System (PS) based on a PV field, an EHP and an electric energy storage. In particular, two energy indexes to evaluate the on-site use of electric energy available from PS are introduced. Furthermore, an energy and environmental comparison between the solar-PV system and the Reference System (CS), based on electric grid, an electric-activated chiller and a natural gas boiler, are introduced here. Both systems will be described in detail in the following paragraphs.

Proposed system evaluation: Methods

One of the major problems of grid-connected PV fields is the electricity feeding the power grid that lead to interferences to it (power quality, voltage regulation, etc.). To limit this interaction, an EES could be added to the PV plant. Two indexes highlighting the on-site use of PV electricity could be introduced in Weniger *et al.* [23]:

- *s*: ratio between on-site use of electricity available from PV plant and the total that the office requires;
- *d*: ratio between on-site electricity supplied by PV plant to the office and total delivered by PV plant.

Energy and environmental analysis: Methods

The energy analysis is based on the comparison of PS and CS introducing Fuel Energy Saving Ratio (*FESR*) parameter, that compares the primary energy input linked to fossil fuel of the conventional ($E_{\mathrm{p}}^{\mathrm{CS}}$) and the proposed ($E_{\mathrm{p}}^{\mathrm{PS}}$) systems. *FESR* can be expressed as eq. (1):

$$FESR = \frac{E_{\mathrm{p}}^{\mathrm{CS}} - E_{\mathrm{p}}^{\mathrm{PS}}}{E_{\mathrm{p}}^{\mathrm{CS}}} \times 100 \tag{1}$$

where primary energy input, due to the fossil fuel, needed by conventional and proposed systems is computed introducing [eq. (2) and eq. (3)]:

$$E_{\mathrm{p}}^{\mathrm{CS}} = E_{\mathrm{p}}^{\mathrm{PP}} + E_{\mathrm{p}}^{\mathrm{B}} = \frac{E_{\mathrm{el}}^{\mathrm{PP}}}{\eta_{\mathrm{el}}^{\mathrm{PP}}} + \frac{E_{\mathrm{th}}^{\mathrm{B}}}{\eta_{\mathrm{th}}^{\mathrm{B}}} \tag{2}$$

$$E_{\mathrm{p}}^{\mathrm{PS}} = E_{\mathrm{p}}^{\mathrm{PP}} - E_{\mathrm{p}}^{\mathrm{grid}} = \frac{E_{\mathrm{el}}^{\mathrm{PP}} - E_{\mathrm{el-exp}}^{\mathrm{grid}}}{\eta_{\mathrm{el}}^{\mathrm{PP}}} \tag{3}$$

where the primary energy input is a function of:

- Primary energy ($E_{\mathrm{p}}^{\mathrm{PP}}$) linked to electric energy imported from the grid ($E_{\mathrm{el}}^{\mathrm{PP}}$) and avoided primary energy ($E_{\mathrm{p}}^{\mathrm{grid}}$) related to electric energy exported to power grid ($E_{\mathrm{el-exp}}^{\mathrm{grid}}$). The electric energy sent to power grid is computed as a credit to evaluate primary energy input of the PS;
- Primary energy needed by the boiler ($E_{\mathrm{p}}^{\mathrm{B}}$) to meet heating load ($E_{\mathrm{th}}^{\mathrm{B}}$).

The environmental analysis is performed evaluating equivalent CO_2 emissions for proposed ($\mathrm{CO}_2^{\mathrm{PS}}$) as well as for reference ($\mathrm{CO}_2^{\mathrm{CS}}$) system.

The CO_2 emissions are estimated introducing CO_2 emissions factors. This parameter, identified by β, is equal to 0.205 kg CO_2 for each kWh of primary energy, if the energy conversion system is fuelled by natural gas. The emission factor for electric energy imported from power grid (α), is 0.360 kg CO_2 per kWh of electricity and was evaluated including the contribution of the fossil fuel activated thermo-electric power plants and the renewable systems [24]. Similarly to *FESR*, ΔCO_2 can be expressed as:

$$\Delta \mathrm{CO_2} = \frac{\mathrm{CO_2^{CS}} - \mathrm{CO_2^{PS}}}{\mathrm{CO_2^{CS}}} \times 100 \tag{4}$$

$$\mathrm{CO_2^{CS}} = \mathrm{CO_2^{PP}} + \mathrm{CO_2^{B}} = \alpha \times E_{\mathrm{el}}^{\mathrm{PP}} + \beta \times E_{\mathrm{p}}^{\mathrm{B}} \tag{5}$$

$$\mathrm{CO_2^{PS}} = \mathrm{CO_2^{PP}} - \mathrm{CO_2^{grid}} = \alpha \times (E_{\mathrm{el}}^{\mathrm{PP}} - E_{\mathrm{el-exp}}^{\mathrm{grid}}) \tag{6}$$

BUILDING AND END USER DESCRIPTION

The building introduced in this study is situated in Naples (Southern Italy), city that is in a climatic zone characterized by 1,034 heating degree days. It is characterized by one floor and by a flat roof, with a floor area of 200 m^2, to which corresponds 600 m^3 in terms of volume. The envelope characteristics of the building are reported in Table 1, the solar heat gain (g-value) for window is 0.75. Thirteen people seated and performing light office working are present in weekdays between 9:00 and 13:00 in the morning as well as in the afternoon between 14:00 and 18:00. There is no occupancy during weekends.

Table 1. Building envelope data

	Transmittance [W/m^{2}K]	Thermal mass [kg/m^2]	Area [m^2]
External wall	0.40	373	135
Roof	0.38	322	200
Ground	0.42	689	200
Window	2.58	-	45

The heating system operates from November 15th to March 31st during weekdays (8:00 to 18:00) ensuring 20.0 °C (+/–0.5 °C) for room air temperature, while it is turned off during the weekends. From June 1st to September 30th, the space cooling system is active and the room air temperature is fixed at 26.0 °C (+/–0.5 °C). Terminal units (fan-coils) working at low temperature are used here to meet space cooling and heating loads. Space cooling and heating demands, which monthly distribution is reported in Figure 1, are 6,453 kWh and 2,920 kWh, respectively. The sanitary hot water demand is not included in this study due to the negligible weight in comparison to space heating demand.

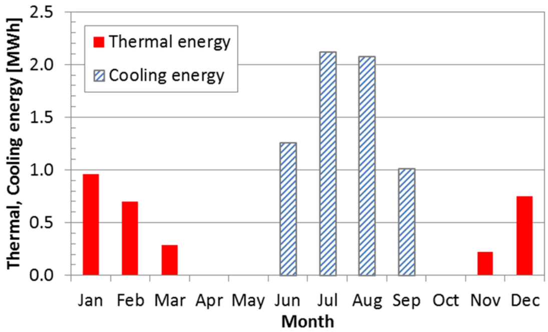

Figure 1. Thermal and cooling demands for each month

Leaving out Heating, Ventilation and Air Conditioning (HVAC) requirements and in accord with an on-site study carried out on the electric energy required by office buildings [25] electricity demand is evaluated taking into account:

- A demand of 29.64 kWh/m^2 on yearly basis considering small power equipment present in the offices (personal computers, printers, monitors, etc.);
- A specific load of 11.74 kWh/m^2 per year due to artificial lighting.

The electric loads, leaving out HVAC demand, reported on Figure 2 are considered introducing three type-days (cooling, heating and intermediate season) for weekdays, and only one type-day for weekends.

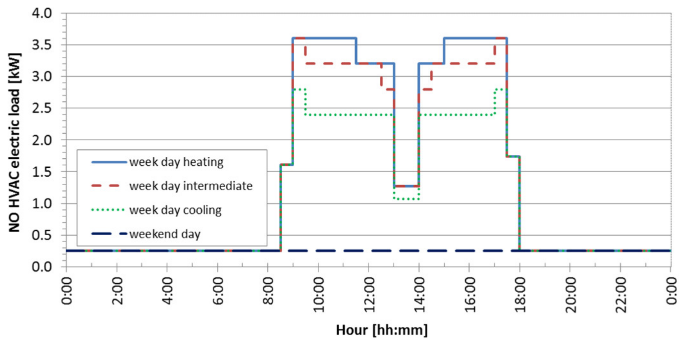

Figure 2. Different electric loads (week days, weekends) excluding HVAC

PROPOSED AND REFERENCE SYSTEM COMPONENTS

This section describes the main components included in the proposed system and introduced to satisfy energy demand of the analysed user. The main characteristics of a conventional system traditionally considered to satisfy final energy demand of a building, are also described. This premise is fundamental because, by identifying the two compared systems (proposed and reference), it will be possible to evaluate the energy conversion efficiency of each component and therefore the primary energy necessary for its activation. In particular, energy as well as environmental analysis reported in the following paragraphs will be based on the evaluation of energy flows reported on the schemes shown in the following Figure 3 and Figure 4. To meet building space cooling and heating loads an EHP activated by PV plant is introduced here as PS. This PS consists of an EHP, PV modules and a DC/AC inverter. The PV plant meets electricity to activate the EHP and the pure electric load of the office (lighting, small power equipment). The PS is connected to power grid and works with it in bidirectional way.

Two scenarios including PV field were analysed:

- PV-EHP: building electricity requirement is directly met by the PV system and the power grid;
- PV-EHP/EES: electricity load is met by the PV field, that includes also the electric storage battery (EES), and the power grid.

The energy conversion system considered as reference (CS) consists of:

- An electric activated chiller (CH), with an EER equal to 3.0 and a rated cooling power of 13.3 kW;
- A non-condensing gas-fuelled boiler (B) with a thermal efficiency ($\eta_{\mathrm{th}}^{\mathrm{B}}$), of 90.2% and a rated thermal power of 24.0 kW [Lower Heating Value (LHV) = 9.52 kWh/Sm^3] analysed in Angrisani *et al.* [26];
- The power grid meets electric load of the office (CH, lights, small power equipment). The Italian power grid efficiency ($\eta_{\mathrm{el}}^{\mathrm{PP}}$) including the thermo-electric power plants, the renewable based power plant contribution, and losses due to distribution and transmission grid is considered equal to 65.5% [27]. Primary energy is evaluated excluding renewable share and considering only the fossil fuel.

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Figure 3 and Figure 4 show the proposed and conventional systems in heating and cooling modes, respectively.

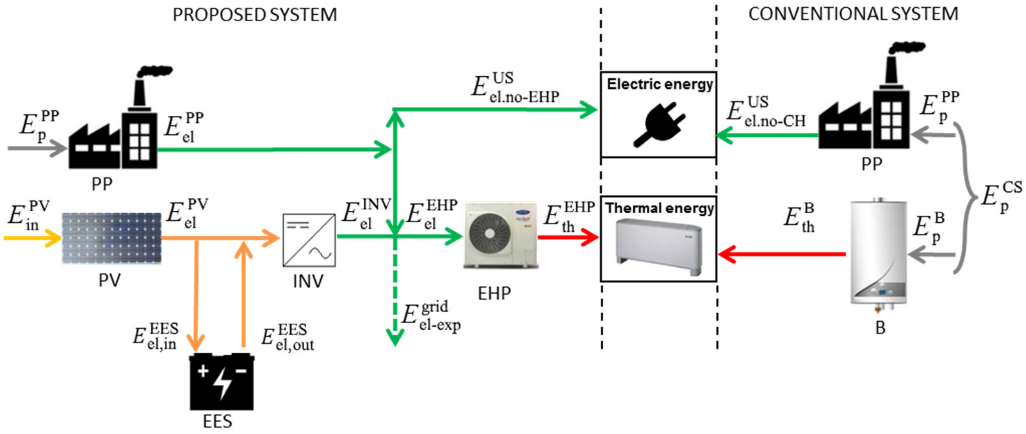

Figure 3. Solar PV and conventional systems in heating period

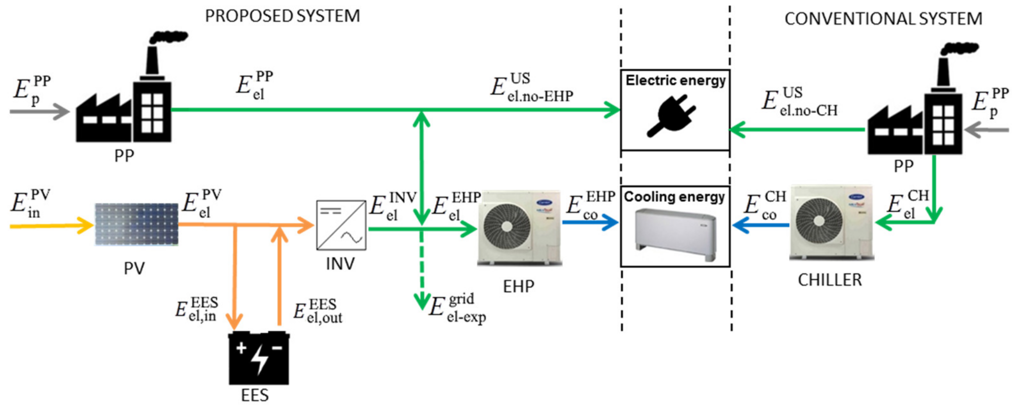

Figure 4. Solar PV and conventional systems in cooling period

To optimize annual electricity production, PV panels facing south have a tilt angle equal to 31°. Furthermore, the analysis was carried out varying the number of solar panels and the peak power (4.5-7.5 kW). Each solar panel has a rated power of 0.25 kW, having a gross area of 1.64 m^2 and efficiency in reference test condition of 15.28%. The inverter parameters, different for each peak power, are reported in Table 2.

Table 2. Inverter characteristics

PV nominal power [kW]	4.50	6.00	7.50
Nominal DC input power [kW]	5.15	6.20	7.65
Nominal AC power [kW]	5.00	6.00	7.50
Maximum efficiency [%]	97.0	97.0	98.0
EURO/CEC weighted efficiency [%]	96.4	96.4	97.5

The EHP considered for PS has a COP of 3.19 and a rated heating power of 14.1 kW, while it has an EER of 3.32 and a cooling nominal power of 13.3 kW. For the second scenario (PV-EHP/EES) an electric energy storage with three different sizes (3.2, 6.4 and 9.6 kWh), an efficiency of 94.0% and a depth of discharge of 90.0% is added. Electric energy demand per year of PS and CS is reported on Table 3. Total electric consumption depends on pure electric load (artificial lights, small power office equipment), EHP and auxiliaries (fans, circulating pumps, etc.).

Table 3. Office electric energy demand on annual basis

Electricity requirements	PS	CS
Small power office equipment [MWh/y]	5.93	5.93
Artificial lights [MWh/y]	2.35	2.35
EHP [MWh/y]	2.57	-
Chiller [MWh/y]	-	1.84
HVAC auxiliaries [MWh/y]	0.79	0.79
Total [MWh/y]	11.6	10.9

MODEL DESCRIPTION

The software introduced for the analysis of the solar based system is TRNSYS 17 [28]. It is usually considered to realize dynamic simulations of energy systems interacting with a building. Each component of the analysed system is characterized through subroutines (types), available in standard and supplementary libraries [29]. The components can be connected to each other to build very complex configurations. Table 4 reports the main components and related types used in TRNSYS project. The 'types' of the most important components are neatly analysed below. PV panels are characterized by 'type 94' [30] that evaluates the current-voltage curves of a single panel starting by an equivalent circuit built considering "four-parameters" available from PV manufacturer data. EHP and CH are simulated starting by their performance maps (type 941, type 955). Gas-fuelled boiler is modelled using 'type 6', which considers a fixed thermal efficiency. The office building is modelled with 'type 56' which can model the thermal behaviour of a building with different thermal areas.

Table 4. Main components and related types used in TRNSYS

Component	Type number	Library
PV panel	94	Standard
Regulator/Inverter	48	Standard
EES	47	Standard
EHP	941	Standard
CH	655	Standard
Boiler	6	Standard
Pump	114	Standard
Multi-zone building	56	Standard
Pipe/Duct	31	Standard
Mixing valve	649	TESS
Diverting valve	647	TESS
Weather data	15	TESS

RESULTS

This paragraph reports the main results obtained on the basis of the methods introduced in the previous paragraph. In particular the analysis is reported considering the proposed system and also comparing this system with the reference one.

Proposed system evaluation: Results

On the basis of different lay-outs PV plant electric efficiency is 14.6% if peak power is equal to 4.5 kW and 6.0 kW, while is 14.7% for 7.5 kW.

Figure 5 reports on annual basis for each PV power and storage capacity the distribution of electricity due to PV plant (on-site use and exported) and imported from electric grid. Electricity from PV is consumed on-site (blue bar) and also feeds the power grid (red bar), while there is an integration from the grid (green bar).

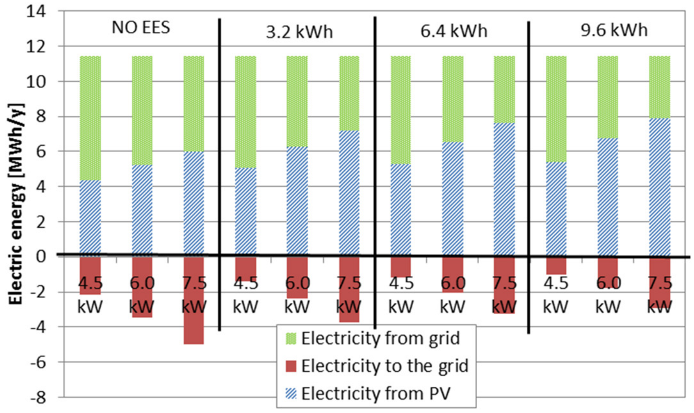

Figure 5. Electric energy distribution as a function of PV rated power and electric storage capacity

In Table 5 the ratios introduced in the previous paragraph, on annual basis and for four configurations, are reported. PV electricity meeting end-user's requirements (*s*), improves with PV rated power and EES size reaching the best result of 0.681 for 7.5 kW and 9.6 kWh. The fraction of on-site use of PV electricity, with respect to the total production (*d*), shows a reduction with PV nominal power while it improves with EES capacity. The configuration with the lowest percentage of electricity exported to power grid, equal to 16.0% (d = 0.840), has 4.5 kW with 9.6 kWh as electricity storage size. A more detailed analysis is reported in Figure 6 that shows on monthly basis the same ratios reported on Table 5.

For each month, with increasing size of PV plant the weight of on-site use of renewable electricity increases. The introduction of an EES leads to a rise of on-site use of electricity, but this effect is less strong for higher sizes of the battery. The month characterized by the highest contribution of PV electricity on the demand is May, due to high renewable electricity availability and no heating and cooling demands. In winter months low production of PV electricity leads to a strong contribution from external grid up to about 80% (4.5 kW, January/December, no EES). Electricity sent to the grid improves with PV size, while the addition of an EES leads to a reduction of this effect. Also with reference to *d* index the addition of an EES improves on-site use of electricity available from PV plant. The highest percentage of electricity exported occurs in intermediate months (April, September), characterized by interesting PV electricity production and no heating and cooling loads.

Table 5. Ratios on annual basis on the on-site use of electric energy available from PV plant

PV size [kW]	Battery capacity [kWh]	*s* [-]	*d* [-]
4.5	No EES	0.375	0.669
	3.2	0.437	0.786
	6.4	0.454	0.818
	9.6	0.465	0.840
6.0	No EES	0.452	0.605
	3.2	0.538	0.726
	6.4	0.565	0.765
	9.6	0.584	0.792
7.5	No EES	0.518	0.548
	3.2	0.618	0.659
	6.4	0.656	0.702
	9.6	0.681	0.730

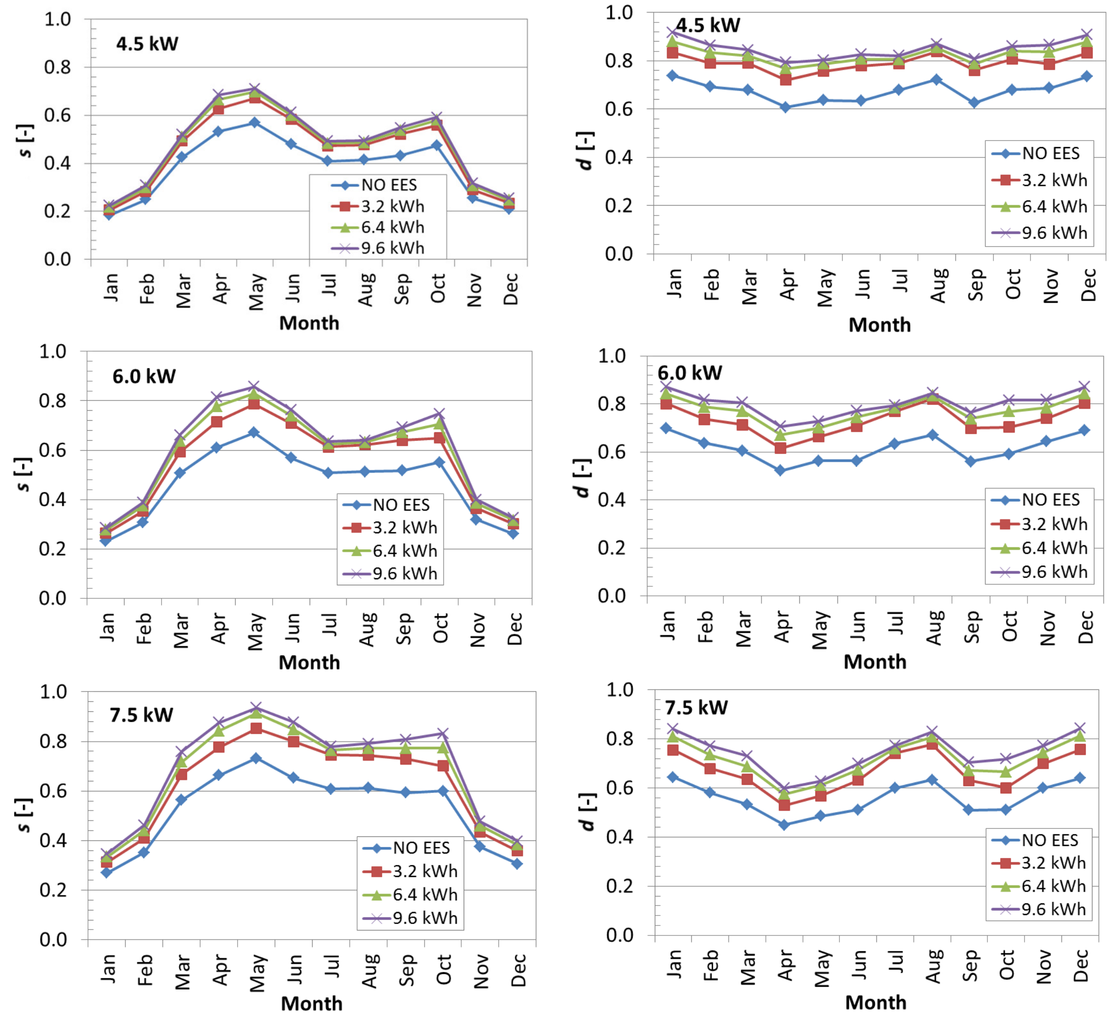

Figure 6. Ratios on monthly basis of on-site use of electricity available from PV plant

Energy and environmental analysis: Results

As highlighted by Table 6, *FESR* improves with PV size thanks to the higher availability of renewable electric energy. It ranges between about 59% (4.5 kW) and about 93% (7.5 kW). ΔCO_2 has a behaviour that is in agreement to *FESR* achieving a peak for each PV power in the configuration without batteries (Table 6). The introduction of electric storage leads to a light reduction, up to about 1%, both for *FESR* and ΔCO_2 for each peak power. The efficiency of the batteries (94.0%) leads to worst performance of the proposed system due to the introduction of further losses. Figure 7 reports reference electric efficiency and equivalent CO_2 emissions factor on monthly basis with reference to Italian grid. It can be noted that during summer period electric efficiency shows the highest values due to the strong contribution of renewable electricity and in particular from PV. For the same months, of course, equivalent CO_2 emission factor reaches the lowest values.

Starting from these parameters an analysis of *FESR* for PV system without batteries on monthly basis is reported on Figure 8. Values higher than 100% depend by PV electricity feeding the grid that for PS in some months is higher that electricity imported from the grid bringing to a negative value for primary energy due to PV-based system [see eq. (3)]. To explain better, the reason why the values could be higher than 100% the contribution of each term appearing in eq. (3) for configuration without battery and 7.5 kW is reported in Table 7. Negative values of primary energy due to proposed system ($E_{\mathrm{p}}^{\mathrm{PS}}$) correspond to electricity exported to the grid higher than electricity imported from

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the grid. In these cases, the numerator of eq. (1) is higher than denominator leading to a *FESR* greater than 100%.

Table 6. *FESR* and ΔCO_2 on annual basis

PV power [kW]	Battery capacity [kWh]	*FESR* [%]	ΔCO_2 [%]
4.5	No EES	59.2	58.4
	3.2	58.9	58.0
	6.4	58.7	57.9
	9.6	58.6	57.7
6.0	No EES	75.6	75.1
	3.2	75.1	74.6
	6.4	74.9	74.4
	9.6	74.8	74.2
7.5	No EES	92.9	92.8
	3.2	92.4	92.2
	6.4	92.1	92.0
	9.6	91.9	91.7

The highest values, due to exported electricity, are in the months of April and May, characterized by the lack of cooling and heating demands and thus by no HVAC electricity demand. Increasing PV peak power proposed system enhances the electricity exported to the grid and thus the *FESR*. A similar behaviour found for *FESR* could be achieved by ΔCO_2. As shown in Table 6 the use of electric storage leads, also on monthly basis, to a light reduction of *FESR* and ΔCO_2 for each peak power.

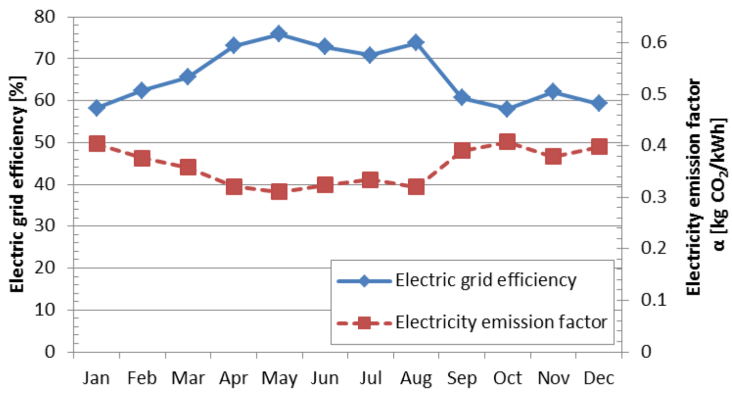

Figure 7. Electric efficiency and equivalent CO_2 emission factor for electricity

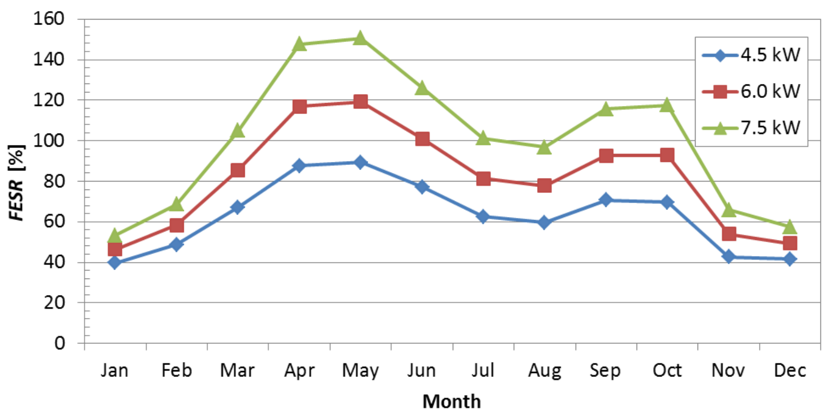

Figure 8. *FESR* for the PV system without batteries as a function of PV rated power and month

Table 7. Primary energy due to fossil fuel related to proposed system

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
E_p^{PP} [kWh]	1,500	1,030	581	332	275	461	700	670	585	536	860	1,238
E_p^{grid} [kWh]	305	405	657	802	795	828	724	611	823	771	344	307
E_p^{PS} [kWh]	1,195	625	−76	−470	−520	−367	−24	58	−238	−235	516	932

CONCLUSIONS

A solar activated electric, cooling and heating system, consisting of a PV field, an EHP and an electric energy storage, introduced to cover electric, space cooling and heating load of a building used for office purpose is analysed here. Dynamic simulations to assess the energy and environmental indexes of the proposed system modifying PV nominal power are investigated. Two lay-outs (PV-EHP, PV-EHP/EES) were considered by means of parameters evaluating the on-site use of PV electricity, as well as primary energy saving and equivalent CO_2 emissions reduction in comparison to conventional reference system. The following results were obtained from the introduction of the proposed system:

- It can be highlighted that on annual basis, PV electricity meeting office demand rises with PV peak power and electric storage capacity, reaching the best result of 0.681 (68.1%) for 7.5 kW and 9.6 kWh. This trend is similar also on monthly basis and in May, due to high PV electricity availability and no heating and cooling loads, the proposed system can cover up 95% of electric energy demand;
- The electricity feeding the grid increases with PV plant size while showing a reduction with electric storage capacity. The configuration representative of the lowest percentage of exported electricity (d = 0.840), is characterized by a PV plant with 4.5 kW including an electric storage of 9.6 kWh. On monthly basis electricity exported is always lower than 50% if there is a battery;
- In terms of primary energy saving and equivalent CO_2 emission reduction, the proposed system always has a better performance than the traditional one, reaching a *FESR* and ΔCO_2 up to 94% for PV-EHP lay-out plant and 7.5 kW. On monthly basis the surplus of PV electricity led to *FESR* and ΔCO_2 higher than 100% while the worst results appear in winter months (40-60%).

Different plant layouts could be considered in future works to evaluate how a thermal energy storage (cold, hot water) introduced in the proposed system can improve the performance of the system as proposed by Toradmal *et al.* [31]. A different way to improve the performance of the system could be the introduction of a demand side management approach to activate the EHP as proposed by Cooper *et al.* [32]. The proposed methodology could be also extended starting by data on electricity mix of power grid available on hourly basis for different European Countries on ENTSO-E Transparency Platform [33]. A further analysis to evaluate the potentiality of the proposed system could be based on economic indexes. The results could be the basis to evaluate the best support economic schemes to be introduced to support renewable based technologies that are traditionally characterized by high investment costs.

NOMENCLATURE

CO_2	equivalent dioxide carbon emissions	[kg CO_2/y]
d	ratio between on-site electricity supplied by photovoltaic plant to the office and total one available from photovoltaic plant	[-]
E	energy	[kWh/y]
s	ratio between on-site use of electricity available from photovoltaic plant and the total one that office requires	[-]

Greek symbols

α	emission factor for power grid electricity	[kg CO_2/kWh$_{el}$]
β	emission factor for natural gas	[kg CO_2/kWh$_{ep}$]
η	efficiency	[-], [%]
ΔCO_2	avoided equivalent CO_2 emissions	[%]

Subscripts

co	cooling
el	electric
el-exp	electric exported
el,no-CH	electricity excluding chiller requirement
el,no-EHP	electricity excluding electric heat pump requirement
in	inlet
out	outlet
p	primary
th	thermal

Abbreviations

B	Boiler	
CH	Chiller	
COP	Coefficient Of Performance	
CS	Conventional System	
EER	Energy Efficiency Ratio	
EES	Electrical Energy Storage	
EHP	Electric Heat Pump	
EV	Electric Vehicle	
FESR	Fuel Energy Saving Ratio	[%]
HVAC	Heating and Ventilation Air Conditioning	
INV	Inverter	
MPPT	Maximum Power Point Tracker	
PP	Power Plant	
PS	Proposed System	
PV	Photovoltaic	
US	End user	

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